

# Superluminal Neutrinos without Revolution

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## Abstract

The velocity anomaly recently reported by the OPERA collaboration appears strikingly at odds with the theory of special relativity. I offer a reinterpretation which removes this conflict, to wit that neutrinos yield a truer measurement of Einstein's limiting speed, and that light and indeed all other matter are retarded by additional interactions with the dark universe. I discuss existing experimental constraints and show that such a notion, considered cosmologically, can be subsumed in the dark-energy equation of state in an expanding Friedman-Robertson-Walker (FRW) universe. Planned measurements of the temporal variation in redshift have the potential to distinguish the possibilities.

The OPERA collaboration has recently observed, with a significance of  $6.0\sigma$  if statistical and systematic uncertainties are combined in quadrature, that neutrinos traverse a known length faster than they would were the speed of light in vacuum assumed [1], signalling an apparent violation of the theory of special relativity. In the face of this extraordinary outcome [2] alternate possibilities must be considered. Let us set aside obvious and admittedly more probable possibilities from the onset: we shall assume that the significance of the experimental result is robust and thus not obviated by unknown systematic errors, and that the OPERA collaboration has measured the group, rather than the phase, velocity of the “muon neutrino” wave packet. The empirical reality of neutrino oscillations [3] complicates the simple picture of a propagating  $\nu_\mu$ ; the propagating mass eigenstates are not those of flavor. Nevertheless, we assume that such details are not important here, so that the apparent violation of special relativity is manifest. In this context, then, is it possible to reconcile the OPERA result with the theory of special relativity? An affirmative answer requires an adjustment in our way of thinking. Consider that terrestrial measurements of the fundamental speed of light are made under conditions in which only known matter is clearly absent, but cosmology tells us we live in a dark-energy and dark-matter dominated universe [4]. I propose that neutrinos interact more weakly with the dark universe than photons and all other known matter do, so that propagating neutrinos offer a better measure of Einstein’s limiting velocity. In this picture the photon remains massless, so that classical electrodynamics is unaltered, but interactions with the dark universe retard its speed slightly. This is tantamount to an index of refraction which differs slightly from unity, so that  $c$  can be less than  $c_\nu$ , the neutrino speed. This possibility is not at odds with special relativity, for the photon speed is measured in a background of dark energy and dark matter, rather than in a vacuum devoid of such content. We know little about the nature of dark matter, and less about dark energy; nevertheless, severe constraints do exist on the nature of the interactions we posit with the dark sector. We consider them carefully in what follows before turning to cosmological tests of the picture we espouse.

*Present Constraints.* — The empirical value of  $c$  is  $2.99792458 \cdot 10^8$  m/s [5]. We employ it as a conversion factor to relate time to distance, and indeed use it to define the meter. Its precise numerical value, however, does not derive from any known fundamental principle, so that it in itself is not sacrosanct. Stringent experimental tests, both terrestrial and cosmological, speak to the nature of the speed of light and hence to constraints on the interactions with the dark universe we propose. Severe limits exist on the variation of the speed of light with frequency [6, 7], as well as on variations in the speed of light with respect to the orientation of its velocity vector in space [8, 9]. Moreover, its universality as a limiting value of speed is also well-established [8, 10]. Thus we suppose the needed interaction must be energy-independent, isotropic, and universal for all matter save neutrinos. Under these conditions the speed of light, determined at the present cosmological time, can remain the same in every inertial reference frame presently accessible to us, albeit  $c < c_\nu$ .

We assert that the speed of light  $c$  and the neutrino limiting speed  $c_\nu$  is related via  $c = c_\nu/n$ , where  $n$  is an index of refraction with  $n > 1$ . In order to make our discussion concrete, we must employ an explicit framework for  $n$ . For definiteness suppose that we have a medium of scatterers, each of mass  $M$ , with mass density  $\rho$ . Employing the conventions and analysis of Ref. [11] we have, for a photon of angular frequency  $\omega$ ,

$$n(\omega) = 1 + \frac{\rho}{4M^2\omega^2} \mathcal{M}_f \quad (1)$$

for  $|n - 1| \ll 1$ , and where  $\mathcal{M}_f$  is the forward Compton amplitude in the scatterer rest

frame. Assuming the discrete symmetries parity, time-reversal, charge-conjugation, as well as Lorentz invariance, unitarity, and analyticity, we have, for energies below particle-production threshold, that  $\mathcal{M}_f = \sum_{j=0} A_{2j} \omega^{2j}$  where  $A_{2j} > 0$  for  $j \geq 1$  [12]. To explain the OPERA data in the face of empirical constraints on the speed of light, we set all  $A_{2j}$  to zero save for  $j = 1$ , so that  $\rho A_2/4M^2$  is set by their result for  $(v - c)/c$ , namely,  $\rho A_2/4M^2 = (2.48 \pm 0.28(\text{stat}) \pm 0.30(\text{sys})) \times 10^{-5} \equiv \delta_0$  [1]. We have posited a background of unknown matter, but our result, namely that the photon sees an index of refraction which differs from unity, can be of broader origin. In particular, the index formula can be generalized to particles of zero mass through the introduction of a thermal bath [13, 14], and the structure of our expansion in  $\omega$  remains unaltered. The stringency of the tests on nonobservation of anisotropies in the speed of light suggest that our “unknown matter” is something other than the dark matter invoked to explain the observed galactic rotation curves.

The OPERA experiment is not the first to study arrival time differences of photons and neutrinos. A previous short baseline experiment was sensitive to deviations in  $|v - c|/c$  to  $|v - c|/c < 4 \times 10^{-5}$  [15], and the MINOS collaboration has reported a measurement of  $|v - c|/c = 5.1 \pm 2.9 \times 10^{-5}$  [16]. The observation of neutrinos from the supernova SN1987A [17] sets a much more stringent limit. The neutrinos were observed to arrive some 3 hours before the first detection of optical brightening to yield a conservative limit of  $|v - c|/c \lesssim 2 \times 10^{-9}$  [18]. The limit implicitly assumes that the initial neutrino and photon pulses were emitted simultaneously, though we do expect the thermal neutrino burst from the core collapse, with neutrino energies of  $\mathcal{O}(10 \text{ MeV})$ , to be emitted prior to the emission of visible light [19]. In Ref. [19] this time difference is assessed at  $\sim 10$  hours, for a red-supergiant progenitor, though taking the OPERA result at face value implies that the neutrino burst associated with SN1987A was emitted some 4 years after optical emission. Such a long time lag is puzzling, and perhaps even implausible, but it must be noted that the detailed mechanism of a core-collapse supernova has not been established [20]. Moreover, SN 1987A in itself had many unusual features — e.g., its progenitor star was a blue supergiant [21]. The observed luminosity was also roughly an order of magnitude smaller than a typical Type II supernova and may be the result of the denser makeup of the star [21]. Although the detected neutrino energies and burst duration appear consistent with their emission in core collapse leading to a proto-neutron-star [22], the pulsar expected in this picture has not yet been observed. Alternate mechanisms are possible [23–25], and features such as rotation of the core-collapse remnant and its associated magnetic fields may also play a role [25]. In a black-hole-accretion-disk scenario, or “collapsar” model [23], e.g., neutrinos are emitted from the edge of the accretion disk formed after the core collapse; they are also of MeV energy scale — and the burst duration can be of comparable duration, though this outcome depends on the parameters of the model, as does whether the core-collapse neutrinos are trapped within the star [26, 27]. Particular features of SN 1987A suggest it may have had a companion star [28] as well; perhaps the dynamics of a binary system help explain the needed time lag and burst duration, with the close association of the observed neutrino and optical bursts attributable to coincidence. Observations of neutrinos from gamma-ray bursts could well yield more discriminating limits [29], but these have not yet been observed.

The need to confirm the OPERA result in an independent experiment is clear. Beyond this, the empirical determination of an energy dependence in the limiting speed of the neutrino would speak to complications beyond the simple picture we propose here. Recently constraints on superluminal models from the mere detection of neutrinos in the OPERA

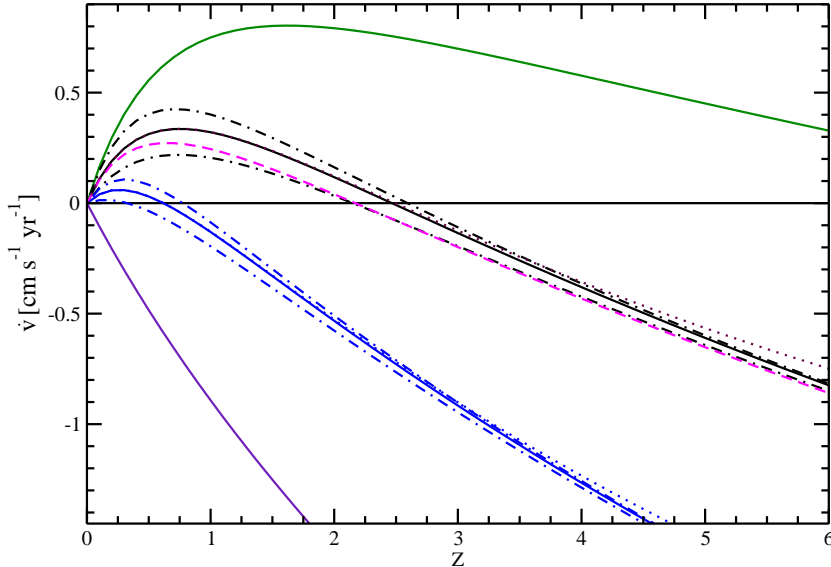


FIG. 1: The change in recession velocity  $\dot{v}$  as a function of redshift  $z$  in various, flat  $\Lambda$ CDM cosmologies, as well as in some alternate scenarios. The solid lines from bottom to top denote  $\Omega_\Lambda = 0, 0.5, 0.729$  (WMAP 7-year “best fit”), and  $0.9$ , respectively, with  $H_0 = 70.3 \text{ km/s/Mpc}$ [42]. The dot-dashed lines bracket the associated solid ones above and below when  $w = -1$  is replaced by  $w = -1.2$  and  $w = -0.8$ , respectively. The dashed curve results when  $w$  is replaced by the  $z$ -dependent function used in Ref. [43] with  $w_0 = -1$  and  $w_a = 0.28$ ; the dotted curves result when the calculation of  $\dot{v}$  is amended by an index of refraction as per the OPERA result.

experiment have been discussed [30–32]. These do not operate in the picture espoused here because Lorentz symmetry is not broken at the level of particle interactions. Pair bremsstrahlung, as discussed in Ref. [30], can nevertheless occur but via an explicit interaction with the medium, much as computed in lepton “trident” production in quantum electrodynamics [33]. The observation of earth-crossing neutrinos in the OPERA energy range and beyond [34] show that the presence of such pair production effects do not constrain our scenario. Confirmation of our particular scenario requires study of the speed of light in temporally different regimes. To realize this, we turn to cosmological studies.

*Time Variation in Redshift.*— The redshift to an object in a universe with matter and dark energy will change with time, and the measurement of its rate of change gives direct access to cosmological parameters [35–37]. The measurement is very challenging, and may well require decades of observing time [36, 37], but with the advent of extremely large telescopes and laser-comb-stabilized calibration of spectrographs [38], it becomes possible [39]. It is useful to recap the standard computation of  $\dot{z}$  [40] before turning to the inclusion of interactions. In an expanding FRW universe, the redshift  $z$  of an object at time  $t_1$  observed at time  $t_0$  is related to the cosmological scale factor  $a$  via  $1 + z = a(t_0)/a(t_1)$ . Differentiating with

respect to  $t_0$  and noting  $dt_1/dt_0 = 1/(1+z)$ , we find [36]

$$\dot{z} \equiv \frac{dz}{dt_0} = H_0(1+z) - H(z), \quad (2)$$

where the spectroscopic velocity shift is given by  $\dot{v} = c\dot{z}/(1+z)$  and  $H(z)$  is given in terms of

$$H(z) = H_0 \left[ \Omega_M(1+z)^3 + \Omega_R(1+z)^4 + \Omega_\Lambda(1+z)^{3(1+w)} + (1 - \Omega_{\text{tot}})(1+z)^2 \right]^{1/2}, \quad (3)$$

where  $\Omega_M$ ,  $\Omega_R$ , and  $\Omega_\Lambda$  represent the fraction of energy density in matter, radiation, and dark energy, respectively, relative to the critical density today. For the region of  $z$  in which the stars and galaxies we observe reside,  $\Omega_R$  is completely negligible, and, moreover, we shall assume a flat cosmology so that  $\Omega_{\text{tot}} = 1$ . The dark-energy density is characterized by an equation of state  $w$ , where  $w = -1$  corresponds to the cosmological constant. The value of  $w$  need not be a constant in  $z$ , and in nonstandard cosmologies the scaling of the  $\Omega_M$  term can also be modified, note Ref. [37] for a discussion. Curves illustrating the evolution of  $\dot{v}$  with  $z$  are shown in Fig. 1. The possibility of light-dark-sector interactions can modify the shapes of these curves in  $z$ . The usual comoving distance is defined in the absence of interactions [41]; to include them via an index of refraction we note that the infinitesimal comoving distance is modified from  $\delta t/a$  to  $n\delta t/a$  as the slowing of the speed of light makes the lightcone travel time longer [11]. Consequently our starting point is modified to

$$1+z = \frac{a(t_0) n(t_1)}{a(t_1) n(t_0)}, \quad (4)$$

where we evaluate  $n(z(t))$ , noting in this case that  $n(z) = 1 + (1+z)^3\delta_0$  [11]. Differentiating with respect to  $t_0$  and noting that  $dt_1/dt_0 = 1/(1+z)$  as before, as well as that  $dz(t_0)/dt_0 = 0$ , yields

$$\dot{z} = \frac{(1+z)H_0 - H(z)}{1 - (1+z)\frac{d \ln n(z)}{dz}} \simeq ((1+z)H_0 - H(z)) \left( 1 + (1+z)\frac{dn(z)}{dz} \right) \quad (5)$$

to leading order in small quantities, where  $\dot{v} = c_\nu\dot{z}/(1+z)$ , though the replacement of the overall factor of  $c$  with  $c_\nu$  in  $\dot{v}$  will always be insignificant as it appears in a product with  $H_0$ . Note  $|n-1| \sim \mathcal{O}(0.1)$  for  $z \sim 10$ . We compare the index-of-refraction-modified result for  $\dot{v}$  with that from the flat  $\Lambda$ CDM model, as well as with other scenarios, in Fig. 1. The inclusion of  $n$  shifts  $\dot{v}$  to greater values with  $z$ , just as a value of  $\Lambda > 0$  itself does [11]. We show, too, how  $\dot{v}$  with  $z$  changes if  $w \neq -1$ . Experimental constraints on  $w$  exist largely for models with constant  $w$ , so that, e.g., the WMAP 6-parameter  $\Lambda$ CDM fit to the 7-year data, combined with data from baryon-acoustic oscillations (BAO) and the measured value of  $H_0$ , yields  $w = -1.10 \pm 0.14$  [42]. In comparison, a direct measurement of the BAO angular scale using a distribution of galaxies with  $z = 0.5 - 0.6$  yields  $w = -1.03 \pm 0.16$  if the other parameters are fixed [43]. This data set also yields a constraint on  $w(z)$ : writing  $w(z) = w_0 + w_a(1 - 1/(1+z))$  and using the WMAP 7-year “best-fit” parameters [42] yields  $w_a = 0.06 \pm 0.22$  [43]. Since the empirical data allow  $w < -1$ , we show how  $\dot{v}$  changes if  $w$  is altered to  $w = -1.2$  or  $w = -0.8$  in Fig. 1, as well as if we employ  $w(z)$  and the WMAP 7-year “best-fit” parameters with  $w_a = 0.28$  [43]. The effect of the modification with  $n$  on  $\dot{v}$  is rather small, though it begins to be appreciable for  $z$  in excess of  $z \simeq 0.3 - 0.4$ . Interestingly this is within the window of Lyman- $\alpha$  forest studies, for which peculiar motions are known

to be negligibly small [39, 44]. If measurements of  $\mathcal{O}(1\text{ cm/s})$  can be made [38], then a decade of observations can resolve differences of  $\mathcal{O}(0.1\text{ cm/s})$  — such a lengthy campaign is being planned [39].

*Conclusions.* — The sobering significance of the OPERA result [1], coupled with decades of successful tests of special relativity [2], prompts us to consider alternatives which can be consistent with both. The experimental result  $c < c_\nu$  need not reflect a breaking of Poincaré invariance but, rather, could speak to light-dark-sector interactions which yield an index of refraction which differs from unity. The interactions must be energy-independent and isotropic and universal to all matter save neutrinos, to be consistent with existing experimental results. Nevertheless, the suggestion can be tested through the measured time-variation in redshift [35–37]; such studies permit the direct assessment of cosmological parameters. We have determined the amendment to  $\dot{z}$  which appears in the presence of an index of refraction. To realize a simple but definite form of  $n(z)$  we have asserted that the photon couples to unknown matter, yielding  $n(z) \sim (1+z)^3$ . Reality could be much richer, and the possibilities include not only interactions with dark energy but also modifications to gravity itself. The interactions of which we speak may also be specific to very low redshift [45]. Alternatively, perhaps  $c_\nu > c$  can mediate additional radiative effects in the very early universe [46]. Moreover, the notion that a cosmologically local speed of light is tied to a dark energy model in which  $w(z) + 1 \neq 0$  is possible irrespective of whether OPERA is correct. The causal velocity itself could change with cosmological epoch, providing a context for the study of the time-dependence of other fundamental constants, such as  $\alpha \equiv e^2/\hbar c$  [47]. Perhaps the OPERA result opens a new window on the dark universe — and the observational studies retain their interest even if it does not. The breadth of the possibilities underscores the importance of the observational measurement of both dark energy and its equation of state in a range of cosmological epochs.

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